Decision Feedback Channel Estimation - A Precursor For Adaptive Data Transmission Management

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1 Abstract

For a significant proportion of the time, a mobile terminal is operating in an area of reasonable signal strength, with limited interference, and any transmission errors can be attributed to multiplicative multipath fading effects rather than additive noise of co-channel interference. Yet under these conditions, the resulting "irreducible error rate floor" is frequently still unacceptably high for practical data transfer, (typically of the order of 1/1000 – 1/100), necessitating the use of error correction coding with the associated throughput penalties. Ideally, under high signal strength conditions, it would be desirable to operate a mobile data system with no coding overhead, thereby maximising data throughput. A means for suppressing or eliminating the irreducible error floor is thus required, if this attractive concept of an 'adaptive transmission system' is to be entertained.

The necessary channel equalisation can be achieved in a number of ways, one highly publicised candidate being the transmission of reference symbols or reference tones along side the data signal, albeit at the expense of additional power, bandwidth and hardware involved in the implementation. This paper presents an alternative technique using the data modulation alone, (ie no additional reference information is required), making use of the fact for a typical irreducible error rate of 1/100, 99/100 of the received symbols are correctly demodulated. Using this information to remove, (reverse), the modulation from the incoming radio signal effectively results in the recovery of an unmodulated carrier component, subject to the multiplicative channel distortion. Filtering this regenerated carrier signal to extract the channel information and minimise noise, results in a signal representative of the system distortion (assuming flat fading), which can be used to effectively cancel most of the distortion on the incoming signal and significantly reduce the irreducible error rate level.

2 Introduction

Most, if not all mobile data systems in operation today are engineered on a worst case scenario. They are designed to deliver data with sufficient integrity (bit, word, or frame error rate statistics), under the extremes of operating conditions, and to this end, extensive use is made of forward error correction coding and/or ARQ protocols. However, for a high proportion of the in service time, this often significant overhead is totally unnecessary, with the radio units operating at reasonable signal strengths or with minimal levels of interference and the raw (uncorrected) error rate could be expected to be of an acceptable level without recourse to error correction.

Under such circumstances, it would clearly be much more efficient to operate an adaptable data transmission system that was able to take account of the propagation conditions and signal quality, and transmit coded or uncoded signals accordingly. For a radio system to function in this ADAPTIVE manner, a measure of signal strength or interference is necessary, together with a means of error detection, coupled with a suitable underlying control strategy between mobile and base-station. This is not a trivial requirement, but by no means impossible with modern trunked data systems. There is however one major problem with the above scenario - namely the assumption that error rate drops with increasing signal strength or a reduction in interference. In practice, this is found not to be the case, with an "irreducible error rate" floor being reached, attributable to multipath fading. The random gain and phase variations generated by a mobile moving through a multipath fading pattern cause errors in the data demodulator, irrespective of signal strength, the distortion being multiplicative, rather than additive in nature.

The level of the irreducible error rate floor depends on the ratio of symbol rate to fading rate, and also on the type of fading encountered. Rayleigh fading is commonly assumed to give the highest probability of error and for the simple case of Differential Phase Shift Keying DPSK, the error floor is at 1/100 for a maximum fade rate of 100 fades/second, and a symbol rate of 2400 symbols/second. This error rate floor increases with fading rate and modulation complexity (M-DPSK), and is usually unacceptably high for data transfer, (bit error rates below 1/100000 are often quoted in system specifications). Thus, high levels of coding are still required to achieve this level of performance. The adaptive protocol cannot therefore be applied in this scenario.

An alternative to coding for overcoming the irreducible error rate, with reduced overhead, relies on removing the multiplicative fading distortion prior to data demodulation. This implies that the fading must be characterised (measured) in some way, and the conventional approach has been to use a transmitted reference, either in the form of symbol insertion [1-2] or reference tone insertion [3-5]. Any multiplicative distortion can be measured using this reference approach, providing that the fading is flat, and contained within the reference 'filter' bandwidth.

Such reference based channel sounding techniques are very effective at removing the irreducible error rate floor, but incur a power, bandwidth and hardware penalty in their implementation. They also often involve a significant processing delay associated with reference location and extraction. An alternative approach, and the one examined in this paper, is to try an extract the channel information from the incoming data carrier itself using a technique termed reverse modulation or decision feedback..

3 Decision Feedback or Reverse Modulation Channel Sounding

The concept behind reverse modulation is based on the knowledge that even with an irreducible symbol error rate as high as 1/100, the majority of symbols, typically greater than 99/100, are correctly demodulated. Thus, through a process of reverse carrier modulation, (using the knowledge of the received symbol states to

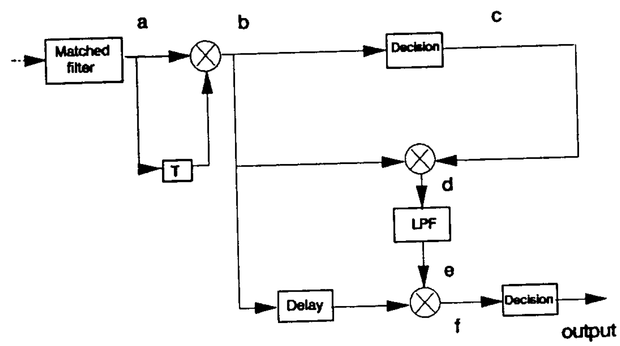

Figure 1: Block diagram of decision-aided DPSK

reverse the transmit modulation process), it is possible to regenerate the carrier (plus multiplicative distortion), almost exactly. (If there were no symbol errors, this process could be exact, and perfect channel estimation achieved, ignoring additive noise). The presence of symbol errors degrades the estimate, however this effect is minimised by utilising the knowledge that the fading process is narrowband, (contained within twice the Doppler frequency ignoring local oscillator errors), and significant filtering (averaging) of the regenerated carrier is possible without removing the channel information, thereby smoothing out the effect of occasional symbol errors - cf. Fig 2.

The reverse modulator concept can be applied for any number of signalling symbol states used, although complexity increases rapidly above 4 level systems. For the sake of brevity, we shall limit further detailed discussion of system performance and application in this paper to the simple case of binary DPSK - DPSK having the attraction of not requiring carrier recovery with the associated delay and complexity.

4 Performance Evaluation of DPSK with reverse modulation channel sounding

A block diagram of the DPSK based system is shown in Fig 1, and an illustration of the reverse modulation concept for this case shown in Fig 2 .

Here the initial symbol estimate is achieved using a conventional DPSK detector, the data decisions then being used to reverse the phase of the differential correlate output at appropriate intervals. Mathematically, the signals at various points in Fig.1 can be expressed as follows:-

$$
\begin{array}{ll}
a: & r_i e^{(a_i+\theta_i)j} \\
b: & r_i r_{i-1} e^{(a_i-a_{i-1}+\theta_i-\theta_{i-1})j} \\
c: & e^{(a_i-a_{i-1})j} \\
d: & r_i r_{i-1} e^{(\theta_i-\theta_{i-1}+\Delta)j} \\
 & \Delta \begin{cases} =0, & \text{correct decision} \\ \neq 0, & \text{wrong decision} \end{cases} \\
e: & r_i r_{i-1} e^{(\theta_i-\theta_{i-1})j} \ \text{(error sample recovered)} \\
f: & r_i r_{i-1} e^{(a_i-a_{i-1})j} \ \text{(phase error eliminated)}
\end{array}
$$

where r_i and θ_i represent the multiplicative distortion, a_i is the information phase.

With perfect reverse modulation, the resulting signal consists of the fading carrier represented in complex baseband notation plus noise, which together are passed through the averaging filter having a bandwidth of 4 times the maximum fade rate, (4 x Doppler). The fading bandwidth is doubled due to the correlation process within the DPSK demodulator. This signal now contains an estimate of the phase change between successive symbols due to fading, which is used to correct for error in the correlate output. A second symbol decision process is now performed on the corrected signal.

Performances of several well-known systems achieved using computer simulation are shown in Fig.3, 4, 5 for operation under static and Rayleigh fading conditions. The ratio of symbol rate to fade rate is 15, corresponding to 160 fades per second at a transmission rate of 2400 symbols per second. The results shown in Fig.3 are the performance of the DPSK system with no phase error (ideal DPSK in Rayleigh fading channel which can be closely approached by reference-based systems), and the performance of decision-aided DPSK with perfect decision feedback (ideal case). For decision-aided DPSK with imperfect decision feedback (representing the practical system), the result is shown in Fig.4. It can be seen that under static conditions, their is negligible degradation of symbol error rate performance in each case, however with fading present, the performance does degrade slightly relative to ideal DPSK alone, with the notable exception that the irreducible error rate is dramatically reduced. The degree of error rate degradation above the IER floor is governed to a large extent by the averaging filter used for fading extraction. Various types of filter are currently under investigation.

Clearly, the reverse modulation technique does eliminate the irreducible error rate phenomena as predicted, with little degradation over the uncompensated

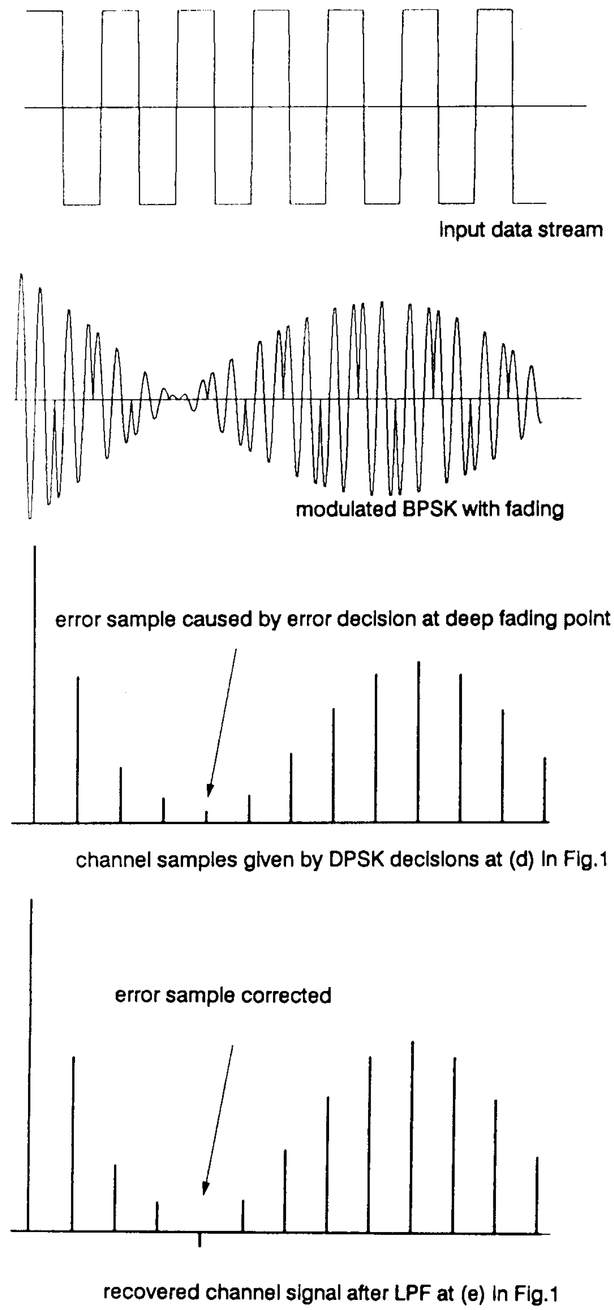

Figure 2: Decision-aided DPSK signals

"parent" demodulator. Similar results are expected for higher level modulation formats. The technique thus opens up the possibility of adaptive data transmission management discussed earlier, for matching and maximising transmission throughput in accordance with channel conditions.

It is interesting to compare the performance of the reverse modulator approach with those of reference based techniques, and also conventional data derived carrier tracking systems utilising Nth power carrier recovery loops. Fig 4 shows the performance of a reference symbol insertion technique for static and fading conditions, with a reference symbol inserted every 8 data symbols. Fig 5 shows the performance of a squaring loop CPSK system, with a post squaring filter having a bandwidth of 4 times the maximum fading rate. In this case, the irreducible error floor is, as expected, worse than that of uncompensated DPSK. It can be seen that the reference based approach does give a better performance in fading than the reverse modulator for DPSK, however, reference symbol insertion, (and equally reference tone insertion), results in a reduction in data throughput, in this case by a factor of 1/8 or 12.5/100, in addition to requiring a more complex transmitter and receiver processing for initial acquisition (location) of the reference symbols/ reference tone.

A further advantage of the reverse modulator approach is evident in applications where system response time is critical. Such a scenario is found in trunked SMR systems where response time on the control channel is necessarily limited. Here the output of the basic 'parent' modulator can be used, albeit with its inferior error rate performance. Where the time constraint is not critical, and the "averaging filter" delay used for channel estimation can be tolerated, the reverse modulator system would be selected.

5 Conclusions

Two main concepts have been introduced in this paper, firstly the notion of adaptive data transmission management to optimise modulation format and coding to channel conditions, and secondly, as a consequence of this strategy, the proposal of a reverse modulation channel sounding technique for elimination of the irreducible error rate floor, which otherwise limits modem performance under good signal conditions.

The adaptive data transmission concept is one which to date has received little attention, but which can potentially increase transmission throughput on a practical data network considerably - providing that a suitable protocol can be established for handling the adaptation process. Work is currently underway at Bristol in this area, specifically looking at adaptive coding techniques.

Reverse modulation, a means for obtaining channel fading information from a data signal without recourse to a separate reference transmission, is shown to be highly effective for the DPSK example given, and work is in progress to evaluate the technique with higher level modulation formats. Its performance is seen to be slightly inferior to a reference-based approach, but with much reduced transmitter complexity, and without the requirement for reference location which is a non-negligible overhead in reference tone or reference symbol insertion techniques. In addition, the reverse modulator concept does not require extra bandwidth or time slots and can thus maximise transmission rate for a given bandwidth allocation.

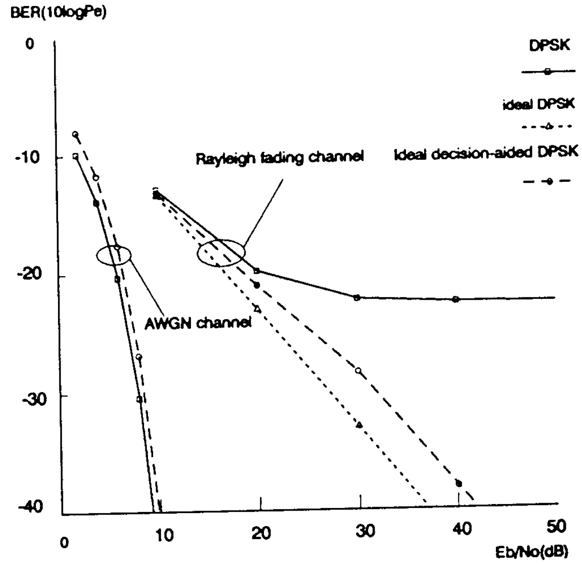

Figure 3: Performance of ideal DPSK (no phase error), ideal decision-aided DPSK (perfect decisions) and real DPSK in both AWGN and Rayleigh fading channel with Dopplar shift = 80 Hz. Bit rate = 2400 bits/s.

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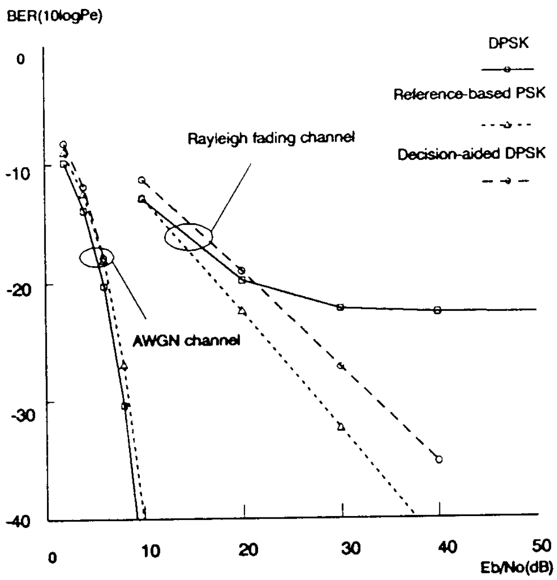

Figure 4: Performance of DPSK, reference-based PSK, decision-aided DPSK in both AWGN and Rayleigh fading channel with Dopplar shift = 80 Hz. Bit rate = 2400 bits/s.

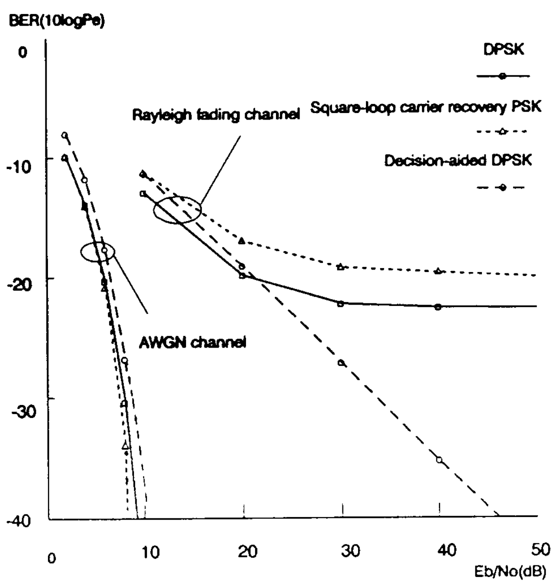

Figure 5: Performance of square-loop carrier recovery PSK, DPSK, decision-aided DPSK in both AWGN and Rayleigh fading channel with Dopplar shift = 80 Hz. Bit rate = 2400 bits/s.

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